

# Carbon footprint of canola and mustard is a function of the rate of N fertilizer

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## Abstract

**Purpose** Best agricultural practices can be adopted to increase crop productivity and lower carbon footprint of grain products. The aims of this study were to provide a quantitative estimate of the carbon footprint of selected oilseed crops grown on the semiarid northern Great Plains and to determine the effects of N fertilization and environments on the carbon footprint.

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**Materials and methods** Five oilseed crops, *Brassica napus* canola, *Brassica rapa* canola, *Brassica juncea* canola, *B. juncea* mustard, and *Sinapis alba* mustard, were grown under the N rates of 0, 25, 50, 100, 150, 200, and 250 kg N ha<sup>-1</sup> at eight environments (location × year combinations) in Saskatchewan, Canada. Straw and root decomposition and various production inputs were used to calculate greenhouse gas emissions and carbon footprints. **Results and discussion** Emissions from the production, transportation, storage, and delivery of N fertilizer to farm gates accounted for 42% of the total greenhouse gas emissions, and the direct and indirect emission from the application of N fertilizer in oilseed production added another 31% to the total emission. Emissions from N fertilization were nine times the emission from the use of pesticides and 11 times that of farming operations. Straw and root decomposition emitted 120 kg CO<sub>2</sub>eq ha<sup>-1</sup>, contributing 10% to the total emission. Carbon footprint increased slightly as N rates increased from 0 to 50 kg N ha<sup>-1</sup>, but as N rates increased from 50 to 250 kg N ha<sup>-1</sup>, carbon footprint increased substantially for all five oilseed crops evaluated. Oilseeds grown at the humid Melfort site emitted 1,355 kg CO<sub>2</sub>eq ha<sup>-1</sup>, 30% greater than emissions at the drier sites of Scott and Swift Current. Oilseeds grown at Melfort had their carbon footprint of 0.52 kg CO<sub>2</sub>eq kg<sup>-1</sup> of oilseed, 45% greater than that at Scott (0.45 kg CO<sub>2</sub>eq kg<sup>-1</sup> of oilseed), and 25% greater than that at Swift Current (0.45 kg CO<sub>2</sub>eq kg<sup>-1</sup> of oilseed). **Conclusions** Carbon footprint of oilseeds was a function of the rate of N fertilizer, and the intensity of the functionality varied between environments. Key to lower carbon footprint in oilseeds is to improve N management practices.

**Keywords** *Brassica juncea* · *Brassica napus* · Carbon footprint · Environment · Greenhouse gas · Nitrogen management · NUE · Yellow mustard

## 1 Introduction

Agriculture involves the production of various crops, the process of various grain products, and the marketing of a variety of food products to the consumers; all these generate greenhouse gases (GHGs) (Dyer et al. 2010). The emissions come from the combustion of fossil energy at various stages of a product's life cycle, giving rise to carbon dioxide (CO<sub>2</sub>). A large portion of the emission from farming practices is nitrous oxide (N<sub>2</sub>O) (Janzen et al. 2006), a gas with about 300 times global warming potential (Forster et al. 2007). In 2008, for example, agriculture in Canada produced approximately 62 million Mg of CO<sub>2</sub> equivalent emissions, accounting for about 8% of Canada's total emissions (Environment Canada 2010). Nearly two thirds of the agricultural emissions occurred as N<sub>2</sub>O, with a large portion of N<sub>2</sub>O coming from the application of nitrogen (N) fertilizer in grain production. Also, various farming practices affect the changes of soil carbon and carbon sequestration (e.g., storage of root biomass), which in turn affects the amount of GHG emissions. Additionally, products of livestock, especially from ruminant animals, release methane (CH<sub>4</sub>) from enteric digestion and N<sub>2</sub>O from decomposing manure.

Farmers are urged to develop effective farming practices to reduce GHG emissions, so that they can strategically lower the C footprints of the products produced on the farm. Carbon footprint was defined by Wiedmann and Minx (2008) as a measure of the total amount of CO<sub>2</sub> emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. This definition, however, did not emphasize the emissions from GHGs other than CO<sub>2</sub>. The fact is that a large amount of GHG emissions associated with farming activities results mainly from N<sub>2</sub>O. Therefore, Gan et al. (2011a) defined the carbon footprint relevant to agricultural products as the total amount of GHG emissions associated with a food product or a service, expressed in carbon dioxide equivalents (CO<sub>2</sub>eq). With this definition, all GHGs were converted into carbon dioxide equivalents.

There are several strategies that can be potentially used to lower the C footprint of field-grown crops (Gan et al. 2011a). One of the promising strategies is to adopt diversified cropping systems where oilseed, legume, and cereal crops are arranged in well-defined crop sequences in rotation systems (Gan et al. 2011b). The diversification of cropping systems with the inclusion of broadleaf crops in cereal-based rotation has been proven not only to increase energy use efficiency (Zentner et al. 2004), decrease pest infestation (Krupinsky et al. 2002), but also to lower C footprints significantly due to reduced use of synthetic fertilizers (Gan et al. 2011b).

Oilseed crops (namely *Brassica napus* canola, *Brassica rapa* canola, *Brassica juncea* canola, *B. juncea* mustard,

and *Sinapis alba* mustard) grown on northern latitudes such as the northern Great Plains of North America and northwest China Plains require adequate N supply for maximum productivity (Karamanos et al. 2007; Malhi et al. 2007a). In sub-humid environments, canola crops responded positively to N fertilizer up to 180 kg N ha<sup>-1</sup> (Brandt et al. 2007). Some hybrid cultivars of *B. napus* canola have a greater response to soil N supply than open-pollinated cultivars under more favorable environments (Brandt et al. 2007; Malhi et al. 2007a). In semiarid areas, *B. napus* canola and *B. juncea* mustard often produce higher seed yields than *B. rapa* canola, *B. juncea* canola, and *S. alba* mustard under normal growing conditions (Gan et al. 2007). Those studies have shown that the seed yield of oilseed species is highly responsible to N fertilizer rates. A level of 100 kg N ha<sup>-1</sup> of fertilization often produces the highest economic return for hybrid *Brassica* crops (Brandt et al. 2007; Karamanos et al. 2007; Malhi et al. 2007a), although the amount of N fertilizer required to achieve the maximum crop yield can vary from 80 to 160 kg N ha<sup>-1</sup> (Cutforth et al. 2009).

There is little information available in the literature regarding the C footprint of oilseed crops grown in semiarid environments, although oilseed crops have become an important component of cropping systems. For example, canola and mustard account for approximately 34% of the total seeded crop land in Canada (Statistics Canada 2010). We hypothesized that the C footprint of oilseed crops was largely dependent on the rate of N fertilizer applied to the crop, while the magnitude of the variation in the value of C footprint was influenced by environmental conditions under which the oilseed crops were produced. This hypothesis was based on the understanding that there are large differences in GHG emissions in oilseed production due to (a) the decomposition of crop straw and roots, (b) the amount of synthetic fertilizers applied to the crop, (c) the use of herbicides and fungicides in crop production, and (d) various farming operations including sowing the crop, spraying pesticides, harvesting crops, and storing harvested products in bins on the farm. Therefore, the objective of this study was to (a) quantify the C footprint of selected oilseed species grown in semiarid environments and (b) determine the effect of the rate of N fertilizer on the C footprint of oilseeds.

## 2 Materials and methods

### 2.1 Field experiments

Field experiments were conducted at eight environments (location–year combinations): Melfort in 2003, 2004, and 2005; Scott in 2004 and 2005; and Swift Current in 2003, 2004, and 2005, all in Saskatchewan, Canada. Those

experimental sites represented the major oilseed production ecoregions (Table 1). Prior to sowing, residual soil available N, P, and S were determined for each of three depths (0–15, 15–30, and 30–60 cm) at each environsite. Eight to 12 soil cores were taken from plot areas and were analyzed for mineral N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ), bicarbonate extractable P, and sulfate-S (Hamm et al. 1970). Five oilseed species were evaluated: *S. alba* yellow mustard (cv. AC Base), *B. juncea* canola (cv. Amulet), *B. juncea* condiment mustard (cv. Cutlass), *B. rapa* canola (cv. Hysyn 110), and *B. napus* hybrid canola (cv. InVigor 2663). These cultivars were representative of each species and were popular among growers on the northern Great Plains at the time the experiment was initiated. The five oilseeds were arranged in a factorial combination with seven rates of N fertilizer (0, 25, 50, 100, 150, 200, and 250 kg N ha<sup>-1</sup>) using a randomized, complete block design with four replicates. Plot size was between 4.8 and 12 m<sup>2</sup>, varying among locations owing to equipment availability. At Melfort, ammonium nitrate was incorporated into the top 38- to 40-mm soil using a shallow rotary tillage prior to seeding, a recommended application method for the site (Malhi and Gill 2004). Immediately after fertilization, the seed was sown between the fertilized rows 20 mm deep using a disc press drill. At Scott and Swift Current, no-till management practices were used to seed oilseeds directly into the field of standing wheat stubble 20 mm deep using a hoe press drill with 25.4 cm row spacing. Urea was mid-row banded to a depth of 40 mm in one-pass operation with seeding. Blends of monoammonium phosphate (11:51:0 of N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O) or triple superphosphate (0:45:0 of N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O) were applied at the same time as N fertilizer. The amount of N from the blend fertilizer application was accounted in the N rate treatments. Weed control was achieved with a pre-seeding or a pre-emergent burn-off treatment with glyphosate, along with recommended post-emergent sprays of grassy and broadleaf weed herbicides applied following label recommendations. Aboveground plant biomass was determined by harvesting 0.5- to 1.0-m<sup>2</sup> area of each plot at maturity. The plant samples were oven-dried at 70°C for 7 to 10 days and weighed. Entire plots were swathed or desiccated at

physiological maturity with an application of glyphosate at label rates. After 7 to 10 days of drying in the field, the swathed windrows were combined with plot-scale equipment and seed and straw mass determined. Root dry weight was estimated using the model development by Gan et al. (2009), where root biomass was a proportion of straw mass with the ratio being changed with water availability.

## 2.2 Residual soil mineral N and crop N use efficiency

In this paper, total residual soil mineral N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) referred to the amount of N measured from the 0- to 60-cm soil depth at seeding time. To facilitate the determination of the effects of residual soil mineral N and applied fertilizer N on the crop productivity and N use efficiency (NUE), we categorized the eight environsites based on the level of residual soil mineral N as low ( $N_{\text{soil}}=20$  kg N ha<sup>-1</sup>), average ( $N_{\text{soil}}=64$  kg N ha<sup>-1</sup>), and high ( $N_{\text{soil}}=180$  kg N ha<sup>-1</sup>). Crop N use efficiency, defined as the seed yield produced per unit of available N, was calculated for each of the three levels of the residual soil N. Total available N was the summation of residual soil mineral N plus fertilizer N applied.

## 2.3 Estimates of carbon footprint

Estimated emissions of GHGs for the production of an oilseed crop included emissions from (1) application of synthetic N fertilizers; (2) crop residue (straw and roots) decomposition; (3) production, storage, and transportation of synthetic N and P fertilizers to the farm gate; (4) production of herbicides and pesticides; and (5) various farm operations such as sowing the crop, spraying pesticides, and harvesting the crop, among others.

When applied to the soil, both synthetic and organic N provide a source for nitrification and denitrification, contributing directly and indirectly to N<sub>2</sub>O emissions (Forster et al. 2007). The amount of direct and indirect emissions is related to the quantity of N applied along with environmental conditions. The magnitudes of these emissions have been studied for Canadian conditions (Gregorich et al. 2005; Rochette et al. 2008). Using a large

**Table 1** Soil type and description for the field experimental sites in Saskatchewan, Canada from 2003 to 2005

Site/ location	Latitude/ longitude	USA soil description	Canadian soil classification	Texture			Organic matter (%)	pH (water paste)
				Class	Sand (%)	Silt (%)	Clay (%)	
Melfort	52°79' N; 104°30' W	Typic Haplocryalf	Gray Luvisol	Loam	40	44	16	3.1
Scott	52°21' N; 108°50' W	Typic Boroll	Dark Brown	Silt clay loam	31	42	27	4.0
Swift Current	50°15' N; 107°44' W	Aridic Haploboroll	Brown	Silt loam	28	49	23	3.0
								7.3

number of observations on measured  $N_2O$  fluxes from Canadian farmland, Rochette et al. (2008) developed a simple, yet reliable model in determining  $N_2O$  emission factors based on a growing season moisture deficit—a linear function of the ratio of growing season precipitation to potential evapotranspiration as follows (Table 2):

$$EF = 0.022P/PE - 0.0048 \quad (1)$$

where EF is the emission factor with a unit of kilograms  $N_2O$ -N per kilogram N and  $P/PE$  is the ratio of precipitation to potential evapotranspiration during the growing season based on long-term weather data. To estimate emissions of

$N_2O$  from nitrate leaching, a fraction of N as total input N needs to be determined. Similarly, Rochette et al. (2008) developed a method to estimate the fraction of N subject to leaching ( $FRAC_{LEACH}$ ) based on  $P/PE$  as follows:

$$FRAC_{LEACH} = 0.3247P/PE - 0.0247 \quad (2)$$

Therefore, using the method developed by the Intergovernmental Panel on Climate Change (IPCC) adopted for Canadian conditions (IPCC 2006), emissions of  $N_2O$  from synthetic N applications can be estimated as follows:

$$CO_2eq_{SNF} = Q_{SNF} \times \{(FRAC_{Gasm} \times EF_{VD}) + EF + (FRAC_{LEACH} \times EF_{LEACH})\} \times \frac{44}{28} \times 310 \quad (3)$$

where  $CO_2eq_{SNF}$  is the total emissions from the synthetic N fertilizer application (kilograms  $CO_2eq$  per hectare),  $Q_{SNF}$  is the quantity of synthetic N fertilizer applied (kilograms N per hectare),  $FRAC_{Gasm}$  is the fraction of synthetic N fertilizer that volatilizes as  $NH_3$ - and  $NO_x$ -N ( $FRAC_{Gasm} = 0.1 \text{ kg N kg}^{-1} \text{ N}$ ),  $EF_{VD}$  is the  $N_2O$  emission factor for volatilized  $NH_3$ - and  $NO_x$ -N ( $EF_{VD} = 0.01 \text{ kg N kg}^{-1} \text{ N}$ ),  $EF_{LEACH}$  is the  $N_2O$  emission factor for nitrate leaching ( $EF_{LEACH} = 0.0075 \text{ kg N kg}^{-1} \text{ N}$ ),  $44/28$  is the conversion coefficient from  $N_2O$ -N to  $N_2O$ , and 310 is the global warming potential of  $N_2O$ .

The quantity of crop residue N ( $Q_{CRD}$ ) is calculated using the aboveground and belowground crop residue biomass multiplied by its respective N concentration. Similar to synthetic N fertilizer applications, emissions

from crop residue decomposition were calculated as follows:

$$CO_2eq_{CRD} = Q_{CRD} \times \{EF + (FRAC_{LEACH} \times EF_{LEACH})\} \times \frac{44}{28} \times 310 \quad (4)$$

It is generally known that the Haber–Bosch process that converts  $N_2$  together with  $H_2$  gases into ammonia ( $NH_3$ ) fertilizers is energy and emission intensive. Lal (2004) conducted an extensive literature review on emissions from manufacturing fertilizers and reported an emission factor of  $4.8 \text{ kg } CO_2eq \text{ kg}^{-1} \text{ N}$  and  $0.73 \text{ kg } CO_2eq \text{ kg}^{-1} \text{ P}_2O_5$  from production, transportation, storage, and transfer of fertilizers

**Table 2** Precipitation and its ratio to evapotranspiration along with emission factors of nitrous oxide and nitrogen leaching factor in the estimate of greenhouse gas emissions in oilseed crops grown on the Canadian prairies

Year	Location	Precipitation							Emission factor (kg $N_2O$ -N $kg^{-1}$ N)	Nitrogen leaching factor
		May (mm)	June (mm)	July (mm)	Aug (mm)	Sept (mm)	Oct (mm)	Total (mm)		
2003	Melfort	49.6	52	35.8	24.4	23.2	26.2	211.2	0.0037	0.10
2004	Melfort	34.1	66	56.4	54	52.4	13.6	276.5	0.0063	0.14
2005	Melfort	36.8	165.4	70	93.6	97	13.8	476.6	0.0144	0.26
1960–2010		40.5	65.3	68.2	52.8	41.1	27.3	295.3	0.0071	0.15
2003	Scott	21.8	34.2	66	44.6	43.4	13.7	223.7	0.0036	0.11
2004	Scott	35.4	53.4	68	44.6	14.8	15.8	232	0.0039	0.11
1960–2010		35.8	66.4	64.8	44.8	30.9	14.6	257.3	0.0049	0.13
2003	Swift Current	41.9	78.7	8.3	20.7	39	20.3	208.9	0.0024	0.10
2004	Swift Current	83.7	66.2	61.1	72.3	27.4	21.5	332.2	0.0067	0.17
2005	Swift Current	22.4	123.2	21.4	52.1	40.7	9.2	269	0.0045	0.14
1960–2010		44.9	74.7	47.5	42.8	33	17.4	260.3	0.0042	0.13

to farm fields. In this paper, we estimated emissions from the production of N and P using the amount of N and  $P_2O_5$  applied on a per hectare basis multiplied by average emission factors (Lal 2004).

Herbicides and fungicides are commonly used in growing oilseeds (Krupinsky et al. 2002). Although emission factors for each individual pesticide are not available at the present time, we assumed that the emissions during processes of production, transportation, storage, and field application were similar among pesticides within a similar category. Thus, an average emission factor of  $23.1 \text{ kg CO}_2\text{eq ha}^{-1}$  was used for herbicides and  $14.3 \text{ kg CO}_2\text{eq ha}^{-1}$  for fungicides, based on active ingredient of a fungicide or herbicide product (Lal 2004). The absolute value of emissions for individual fungicides and herbicides calculated using these factors may vary, since the emissions associated with the production of each product may differ. However, the relative values of the C footprint estimated for different oilseed crops were reasonable because the portion of the C footprint contributed by pesticides is generally small (Gan et al. 2011b).

The emissions associated with various farming operations such as sowing, spraying, windrowing, and harvesting oilseed crops were estimated using a factor of  $14 \text{ kg CO}_2\text{eq ha}^{-1}$  for no-till planting,  $5 \text{ kg CO}_2\text{eq ha}^{-1}$  for herbicide and fungicide spraying, and  $37 \text{ kg CO}_2\text{eq ha}^{-1}$  for harvesting (Lal 2004). With the above estimates, we were able to determine (a) total emissions per unit of areas for the production of oilseed crops, expressed as kilograms  $\text{CO}_2\text{eq}$  per hectare and (b) C footprint as emissions per kilogram of grain produced under the specific growing conditions, expressed as kilograms  $\text{CO}_2\text{eq}$  per kilogram of seed.

## 2.4 Statistical analysis

Data were analyzed using the PROC MIXED model of SAS (Littell et al. 1996) where N fertilizer rate and crop type (i.e., various canola and mustard species/cultivars)

were designated as fixed effects and blocks as random effects. In the analysis, N fertilizer was considered a class variable, whereas the various rates of N fertilizer were considered a continuous variable. Therefore, all interactive responses of crop types and environments to the various N rates were determined by performing linear and non-linear regressions in the analysis of variance. Following the ANOVA analysis, covariance analysis was performed to determine the relative importance of variances with several environment-related factors being considered as covariables. Many environmental factors may have affected the crop productivity and NUE. After analyzing several of the environment-related variables, we found that the amounts of residual soil mineral N and June–July rainfall were the most responsible to oilseed crop yield and NUE. Therefore, these two variables were considered as main covariables in determining the interactive effect of environmental factors and the applied treatments on oilseed productivity and NUE. Treatment effects were declared significant at  $P < 0.05$ .

## 3 Results

### 3.1 Net productivity and N use efficiency

Detailed results on net productivity, yield differences, and yield stability for the five oilseed species have been discussed in previous publications (Gan et al. 2007, 2008). To facilitate the estimate of C footprints, we present a summary of mass productivity and NUE here (Table 3). In brief, seed yield differed significantly among the five oilseed crops evaluated, with *B. napus* canola and *B. juncea* mustard achieving the highest seed yield, both producing 35% greater seed yield than the lowest yielding *S. alba* mustard and *B. rapa* canola (see Table 3). The differences in straw biomass and root biomass among the five oilseed species followed a similar trend to seed biomass. The difference between the

**Table 3** Seed yield, straw yield, and root biomass, as well as mean N use efficiency at environments with low-, average-, and high-yield potentials for five oilseed species/cultivars grown in Saskatchewan, Canada, 2003–2005

Oilseed crop species	Cultivar	Yield/biomass <sup>a</sup>			NUE at environments with yield potentials		
		Straw (kg ha <sup>-1</sup> )	Seed (kg ha <sup>-1</sup> )	Roots <sup>b</sup> (kg ha <sup>-1</sup> )	Low (kg seed kg <sup>-1</sup> N ha <sup>-1</sup> )	Average (kg seed kg <sup>-1</sup> N ha <sup>-1</sup> )	High (kg seed kg <sup>-1</sup> N ha <sup>-1</sup> )
<i>S. alba</i> mustard	AC Base	4,073	1,368	803	12	18.7	26.7
<i>B. juncea</i> canola	Amulet	4,358	1,592	855	11.8	21.8	33.8
<i>B. juncea</i> mustard	Cutlass	4,445	1,842	869	16.2	24.9	35.2
<i>B. rapa</i> canola	Hysyn 110	3,915	1,433	773	11.6	20.1	30.1
<i>B. napus</i> canola	InVigor 2663	5,053	1,886	995	14.4	26.4	40.7
LSD <sub>0.05</sub>		252	102	65	1.9	1.2	2.9

<sup>a</sup> Means across eight environments

<sup>b</sup> Root biomass was estimated based on the model developed by Gan et al. (2009)

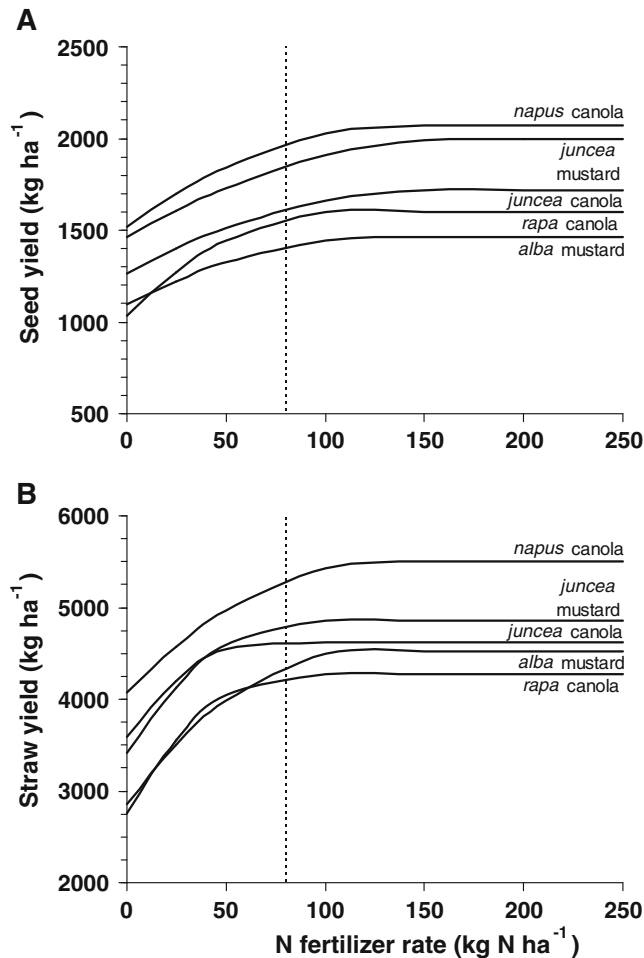
lowest and highest yielding oilseeds was  $490 \text{ kg ha}^{-1}$  for seed yield,  $1,153 \text{ kg ha}^{-1}$  for straw yield, and  $221 \text{ kg ha}^{-1}$  for root biomass.

There was a significant interaction between crop and environment in affecting NUE (see Table 3). At environsites with low- to average-yielding potentials, the *S. alba* mustard, *B. juncea* canola, and *B. rapa* canola had lower NUE than the *B. juncea* mustard and *B. napus* canola. At environsites with high-yielding potential, however, *B. napus* canola had an NUE value of  $40.7 \text{ kg ha}^{-1}$  per  $\text{kg N ha}^{-1}$ , or 14% greater than NUE for the *B. juncea* mustard, both being greater than the three other species. The hybrid cultivar of *B. napus* canola was the most sensitive to the gradient of productivity.

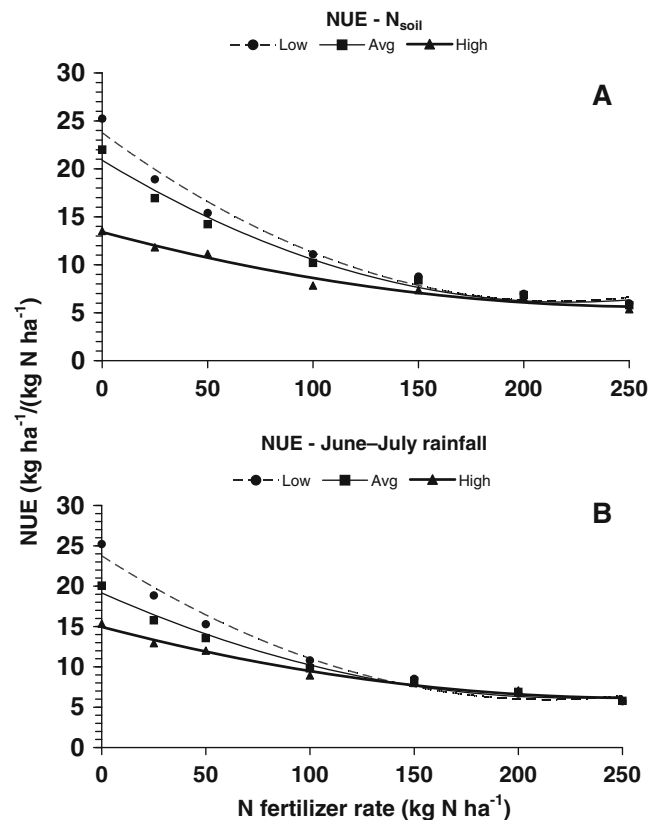
The segmented quadratic-plateau model revealed that both seed yield and straw biomass responded to N fertilizer rates in a curvilinear manner (Fig. 1). Seed yield increased sharply with increasing N fertilizer rate up to  $100 \text{ kg N ha}^{-1}$

(see Fig. 1a), and thereafter, the yield response to fertilizer N rate generally leveled off or the rate of yield increase declined. The response of straw biomass to N fertilizer rate followed a similar trend as that of seed yield, although sharp increases in straw biomass occurred at N rate was between 0 and  $50 \text{ kg N ha}^{-1}$  (see Fig. 1b); thereafter, the rate of increase in straw biomass with increasing N rate declined before  $100 \text{ kg N ha}^{-1}$ .

Nitrogen fertilizer had significant linear and quadratic effects ( $P < 0.001$ ) on NUE; as N rate increased, NUE decreased significantly (Fig. 2). This effect was interacted with the level of residual soil mineral N ( $N_{\text{soil}}$ , see Fig. 2a) as well as with the June–July rainfall (see Fig. 2b). The interactive effect was reflected on the decreasing linear and quadratic coefficients as  $N_{\text{soil}}$  increased from low ( $N_{\text{soil}} = 20 \text{ kg N ha}^{-1}$ ) to average ( $N_{\text{soil}} = 64 \text{ kg N ha}^{-1}$ ) and to high ( $N_{\text{soil}} = 180 \text{ kg N ha}^{-1}$ ). At a given rate of N fertilizer, oilseed crops had a lower NUE at the higher  $N_{\text{soil}}$  sites compared with lower  $N_{\text{soil}}$  sites. Similarly, the effect of N fertilizer rate on NUE interacted with the amount of June–July rainfall (see Fig. 2b). The slope of the NUE regression against N rates at the high (250 mm) rainfall site was  $b = 0.068$ , much



**Fig. 1** Non-linear regression for **a** seed yield and **b** straw biomass produced by *S. alba* mustard (cv. AC Base), *B. juncea* canola (cv. Amulet), *B. juncea* mustard (cv. Cutlass), *B. rapa* canola (cv. Hysyn 110), and *B. napus* canola (cv. InVigor 2663), grown on the Canadian prairies. The vertical dash line indicates the recommended rate of N fertilizer ( $80 \text{ kg N ha}^{-1}$ ) for oilseed production under normal growing conditions



**Fig. 2** Polynomial regression trend lines of N use efficiency ( $\text{NUE} = \text{seed yield}/\text{total available N}$ ) measured at environsites with **a** low, average, and high levels of soil residual N ( $N_{\text{t}}$ ) and **b** low, average, and high June–July rainfall. The data were averages of five oilseed crops grown in Saskatchewan, Canada, 2003 to 2005

smaller than the slopes at the moderate (178 mm) ( $b=0.115$ ) or low (100 mm) rainfall sites ( $b=0.166$ ). The higher the June–July rainfall was, the lower the NUE of the oilseed crops.

### 3.2 Main contributors to greenhouse gas emissions

Covariance analysis revealed that total GHG emissions associated with the production of oilseed crops in semiarid environments were primarily contributed by N fertilization which accounted for 85% of the variation in the estimated emissions and followed by environments which accounted for 11% of the total variation (Table 4). Therefore, further detailed analyses were conducted to determine the effects of the rate of N fertilizer and environments on the total emission and the C footprint of oilseed crops.

Total GHG emissions varied significantly between years in which the oilseed crops were evaluated (Table 5). Averaged across the five oilseed species, the crops grown in 2005 had total emission of 1,420 kg CO<sub>2</sub>eq ha<sup>-1</sup> which was 20% greater than emissions in 2004 (1,190 kg CO<sub>2</sub>eq ha<sup>-1</sup>) and 46% greater than emissions in 2003 (980 kg CO<sub>2</sub>eq ha<sup>-1</sup>). Test locations (i.e., site) also had a significant effect on total GHG emission (see Table 5). The oilseed crops grown at the more humid Melfort site had an averaged total emission of 1,355 kg CO<sub>2</sub>eq ha<sup>-1</sup> which was 30% greater than emissions at the drier sites of Scott and Swift Current. The five oilseed species evaluated in the study showed a similar response within the same test years or sites, and thus, the averages of the five oilseeds were presented for each year and each site (see Table 5).

Nitrogen, phosphorous, and pesticides are the main inputs in the production of oilseed crops in semiarid northern latitudes. Estimated emissions from the production, transportation, storage, and delivery of 100 kg N ha<sup>-1</sup> of N fertilizer to farm gates accounted for 42.5% of the total emissions (see

Table 5), and the direct and indirect emission from the application of 100 kg N ha<sup>-1</sup> of N fertilizer (currently recommended N fertilization rate in oilseed production) added another 30.9% to the total emission. Among the various inputs, the application of N fertilizer resulted in the lowest emission of 204 kg CO<sub>2</sub>eq ha<sup>-1</sup> at Swift Current in 2003 and the highest of 845 kg CO<sub>2</sub>eq ha<sup>-1</sup> at Melfort in 2005. Averaged across eight environments, the use of N fertilizer emitted GHGs that were 17 times the emission from the use of phosphorous, nine times the emission from pesticides, and 11 times the emission from farming operations.

Emissions associated with various farming operations in the production of oilseed crops accounted for <10% of the total emissions (Table 6). In the study, the oilseed crops were grown using no-till management practices, where all fertilizers were applied at the time of sowing the crop in a single pass (with a few exceptions). Sowing the oilseed crops emitted 14 kg CO<sub>2</sub>eq ha<sup>-1</sup>, of which about 1/3 of the emissions was from windrowing and harvesting the crop where a grain truck was operated together with a combine.

Straw and roots were left in the field after the oilseed crops were harvested. The decomposition of the remaining crop residues provided an N source for nitrification and denitrification, contributing direct and indirect emissions totaling 120 kg CO<sub>2</sub>eq ha<sup>-1</sup>, or 10% of the total emission (see Table 6). The amounts of direct and indirect emission varied among environments, largely influenced by total biomass of the straw and roots. The greater the amounts of straw and root biomass were, the higher the total emission due to crop residue decomposition.

### 3.3 Carbon footprint and N fertilizer rates

Covariance analysis revealed that C footprint, expressed as kilograms CO<sub>2</sub>eq per kilogram of seed, was a function of

**Table 4** Summary of covariance of analysis for total emission and carbon footprint for oilseed crops grown at various rates of N fertilizer at eight environmental sites (location–year combinations) in Saskatchewan, Canada

Source	Total emission (kg CO <sub>2</sub> eq ha <sup>-1</sup> )			Carbon footprint (kg CO <sub>2</sub> eq kg <sup>-1</sup> of seed)		
	DF	SS	% Variation	DF	SS	% Variation
ENV	7	21,127,266	10.5223	7	6.49	10.0917
REP(ENV)	32	88,328.96	0.0443	32	5.12	1.9614
Crop	4	6,728.96	0.6743	4	5.06	6.2614
N	1	171,214,153	85.2312	1	47.51	73.8765
N×N	1	665.65	0.0003	1	0.02	0.0310
N level	4	5,335.83	0.0026	4	0.02	0.0310
N×crop	4	8,261,008.3	4.1121	7	2.22	3.4520
N×N×ENV	7	1,553.4	0.0007	7	0.03	0.0466
ENV×N level	28	15,610.35	0.0077	28	0.09	0.1399
Seed mass	1	4,698.94	0.0023	1	1.32	2.0525
Crop residues	1	174,929.99	0.0870	1	0.02	0.0310
Total	190	200,893,550	100	190	64.31	100

ENV environments

**Table 5** Total emission and emissions due to N fertilization for oilseed crops fertilized at the rate of 100 kg N ha<sup>-1</sup>, a recommended rate for oilseed production on the Canadian prairies

Location	Year	Total emission (kg CO <sub>2</sub> eq ha <sup>-1</sup> )	Emission from N fertilizer production		Emission from N fertilizer application		% (prod.+appl.)
			kg CO <sub>2</sub> eq ha <sup>-1</sup>	%	kg CO <sub>2</sub> eq ha <sup>-1</sup>	%	
Melfort	2003	997	477	47.8	266	26.7	74.5
	2004	1,293	477	36.9	409	31.6	68.5
	2005	1,776	477	26.9	845	47.6	74.5
Scott	2003	1,030	477	46.4	264	25.6	72.0
	2004	1,069	477	44.6	281	26.2	70.9
Swift	2003	897	477	53.2	204	22.7	75.9
	2004	1,195	477	39.9	439	36.7	76.6
	2005	1,072	477	44.5	318	29.7	74.2

the rate of N fertilizer, and the magnitude of the effect was influenced by environments and varied with oilseed species (see Table 4). Overall, the C footprint of oilseeds increased slightly as the rate of N fertilizer increased from 0 to 50 kg N ha<sup>-1</sup>, and the further increase of N fertilizer beyond 50 kg N ha<sup>-1</sup> increased the C footprint substantially (Fig. 3a). As the N fertilizer rate increased from 50 to 250 kg N ha<sup>-1</sup>, the C footprint increased at a rate of 0.57 U/100 kg N increase for *S. alba* mustard, 0.53 for *B. rapa* canola, 0.50 for *B. juncea* canola, 0.46 for *B. napus* canola, and 0.38 for *B. juncea* mustard. At a given rate of N fertilizer, the C footprint was the lowest for *Brassica napus* and *B. juncea* canola, the highest for *S. alba* mustard and *B. rapa* canola, and intermediate for *B. juncea* mustard.

Similar curvilinear functions between C footprint and N rates were found for the oilseed crops grown at various sites (see Fig. 3b). At all sites, oilseeds increased C footprints slightly as the rate of N fertilizer increased from 0 to 50 kg N ha<sup>-1</sup>, and the further increase of N rates significantly increased the C footprint. At a given N rate, the oilseeds

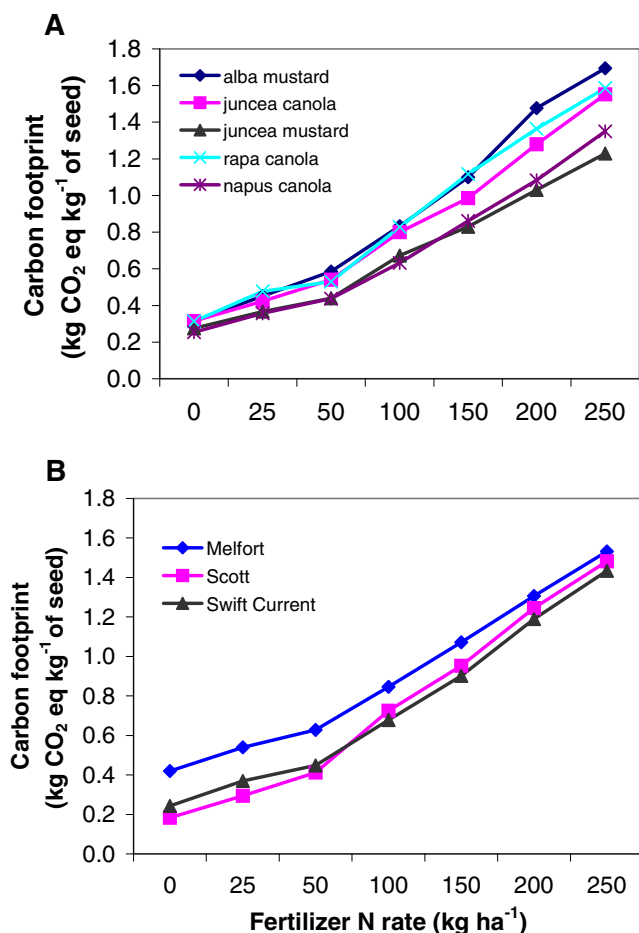
grown at the more humid Melfort site had their C footprint significantly greater than the values at the drier sites—Scott and Swift Current.

#### 4 Discussion

Improved farming practices are required for providing high-quality, affordable food in sufficient quantity while minimizing negative environmental impacts (Liebig et al. 2007). Research has shown that the adoption of diverse cropping systems where various crop species are arranged in well-designed crop sequences has great environmental advantages over conventional monoculture farming systems. Use of diverse cropping systems can reduce production inputs (Zentner et al. 2001), decrease pest infestation (Krupinsky et al. 2002), improve water use efficiency (Miller et al. 2003), and increase net productivity of crops (Tanaka et al. 2007). Oilseeds are the major crops for the crop diversification. For example, the production of canola and mustard on the

**Table 6** Emission from crop residue decomposition, pesticide use, and various farming operations, as well as carbon footprints for oilseed crops fertilized at the rate of 100 kg N ha<sup>-1</sup>, a recommended rate for oilseed production on the Canadian prairies

Location	Year	Emission from crop residue decomposition		Emission from			Carbon footprint kg CO <sub>2</sub> eq kg <sup>-1</sup> of seed
		kg CO <sub>2</sub> eq ha <sup>-1</sup>	%	Pesticides kg CO <sub>2</sub> eq ha <sup>-1</sup>	Operations	%	
Melfort	2003	40	4	91	101	21.5	0.966
	2004	193	14.9	91	101	16.6	0.782
	2005	240	13.4	91	101	12.1	0.788
Scott	2003	104	10	91	68	18	0.548
	2004	126	11.8	91	68	17.4	0.902
Swift Current	2003	39	4.3	91	68	19.8	0.582
	2004	110	9.2	91	68	14.2	0.622
	2005	99	9.2	91	68	16.6	0.830



**Fig. 3** Carbon footprint of oilseed crops was a function of the rate of N fertilizer for **a** the different crop species and **b** oilseeds at different test sites in Saskatchewan, Canada

Canadian prairie has increased from 2 million ha in 1990 to near 8 million ha in 2009 (Statistics Canada 2010), accounting for about 30% of the total cropland. However, little has been studied about the environmental implications of the production of oilseed crops. There exists an urgent need to determine the comparative GHG emissions on a per-area basis and the intensity of C footprints of oilseeds produced under various management practices (Osborne et al. 2010). Rising awareness of energy security issues and climate change has especially spurred an interest in quantifying C footprint per kilogram of grain produced (Wiedmann et al. 2006). Carbon footprint is considered a new farm management indicator and can be the focal point in the evaluation of environmental legislative actions, giving the basis to assess how damaging or beneficial a particular industry is to the environment (Weinheimer et al. 2010). There is a knowledge gap on this subject, and our analyses on the C footprint of oilseeds grown in semiarid environments may be the beginning to fill the gap.

When oilseeds are harvested, their straw is left on the soil surface under no-till management or incorporated into the soil

under conventional tillage management practices. Straw and roots serve as an important N source in the soil for nitrification and denitrification, contributing directly and indirectly to N<sub>2</sub>O emissions (Forster et al. 2007). In our study, the decomposition of oilseed crop straw and roots contributed 10% of the total C footprint. In a previous study, we estimated that straw and roots in durum wheat contributed about 25% of its C footprint (Gan et al. 2011b). The large difference between oilseeds and durum wheat is durum wheat having a greater straw and root biomass (>5,200 kg ha<sup>-1</sup>) than canola or mustard (<4,400 kg ha<sup>-1</sup>) under a similar environment. The amount of emissions from the decomposition of crop residues involves several factors, including the net productivity of the crop (Forster et al. 2007), N concentrations of the plant residue (Janzen et al. 2003), and environmental conditions such as soil moisture and temperature (Flynn et al. 2005; Merrill et al. 2007).

Fossil fuels are the prerequisite at the various stages of fertilization. Using the IPCC methodology (IPCC 2006) adopted for Canadian conditions (Rochette et al. 2008), we estimated that synthetic N fertilizers used in the production of canola and mustard contributed the greatest percentage to the C footprint, averaging 74% of the total emissions, of which 29% coming from direct and indirect emissions through volatilization of NH<sub>3</sub> and NO<sub>x</sub> and leaching of nitrate from the application of N fertilizers in the field. The remaining 45% of the emission came from the production, transportation, storage, and delivery of N fertilizers to farm gates prior to farm use. Our study also showed that C footprint of oilseeds was a function of N rates applied to the crop. Fertilizer N above 50 kg N/ha increased both seed yield and C footprints. Fertilizer N above 100 kg N/ha led to no beneficial effect on oilseed yields but contributed significantly to increased carbon footprints. These results imply that the key to lower the C footprint of canola and mustard is to improve N management practices through reducing N fertilizer application or increasing seed yields and improving N use efficiency through adoption of best cropping practices. Studies have shown that use of hybrid canola cultivars can increase seed yield by 10% to 30% over conventional open-pollinated (OP) cultivars at the recommended fertility rate (Grant and Bailey 1993; Malhi et al. 2007a). Hybrid canola plants utilize applied N more efficiently than OP cultivars (Malhi et al. 2007a). Use of optimized seeding rates can increase canola yield up to 18% under high (120 kg N ha<sup>-1</sup>) fertility levels (Brandt et al. 2007; Karamanos et al. 2005). In drier areas, hybrid canola plants often extract more water from deeper soil layers than other *Brassica* crops (Liu et al. 2011). A balanced N/S ratio in fertilization may help optimize oilseed yield especially in soils with S deficiency (Malhi et al. 2007b).

The intensity of the emission associated with fertilizer application was interacted with environmental conditions.

Among environment-related factors, the ratio of precipitation to potential evapotranspiration ( $P/PE$ ) during the growing season played a major role in affecting oilseed C footprint. The fraction of synthetic N fertilizer and crop residue N that are subject to nitrate leaching and subsequent emissions is also proportional to the  $P/PE$  ratio (Rochette et al. 2008). In our study, the emissions associated with the N fertilization in the production of canola and mustard were 845 kg CO<sub>2</sub>eq ha<sup>-1</sup> at the Melfort site in 2005, 4.2 times the emissions of the same oilseeds grown at Swift Current in 2003 (204 kg CO<sub>2</sub>eq ha<sup>-1</sup>). The Melfort site had an emission factor of 0.09700 kg N<sub>2</sub>O-N kg<sup>-1</sup> of N with a leaching factor of 0.26, both being substantially greater than the same factors for the Swift Current site. Similarly, previous research estimated that the C footprint of spring wheat was at 0.383 kg CO<sub>2</sub>eq kg<sup>-1</sup> of grain produced in the drier Swift Current area, 32% lower than the C footprint (0.533 kg CO<sub>2</sub>eq kg<sup>-1</sup> of grain) of the same wheat crop grown in the more humid Melfort site (Gan et al. 2011a).

## 5 Conclusions

The agricultural sector was responsible for approximately 8% of the total GHG emissions in Canada excluding all emissions from on-farm energy uses. The development of potential mitigation strategies must consider grain crops, the largest commodity, in this sector. Our study demonstrated that the C footprint of oilseeds (mainly canola and mustard) was a function of the rate of N fertilizer applied to the crop. Nitrogen production and application together contributed 74% of the total emission accumulated during the course of the crop production. As the rate of N fertilizer increased from 0 to 50 kg N ha<sup>-1</sup>, the C footprint of the oilseeds increased slightly, but once the rate of N fertilizer was greater than 50 kg N ha<sup>-1</sup>, substantial increases in C footprints occurred. Such curvilinear relationship between C footprint and N rate existed for all five oilseed species evaluated. Variation in environments contributed 10% to the variation in oilseed C footprint. The oilseeds grown at the more humid Melfort site had their C footprint averaged 0.52 kg CO<sub>2</sub>eq kg<sup>-1</sup> of seed, 45% greater than the C footprint at Scott (0.45 kg CO<sub>2</sub>eq kg<sup>-1</sup> of seed) and at Swift Current (0.45 kg CO<sub>2</sub>eq kg<sup>-1</sup> of seed). To lower C footprint of oilseed crops, one must adopt best strategies and practices to reduce N fertilizer use and enhance N use efficiency in the production of oilseeds. The absolute values of the emission estimated for the production of oilseeds will vary, depending on the choice of set boundaries. In the present study, the system boundaries were defined as the period of the life cycle between all production inputs (such as fertilizers, pesticides, seeds) delivered to farm gates and the oilseed crops harvested and the grain products stored in

bins on the farm. These GHG emissions include CO<sub>2</sub> emitted through the combustion of fossil energy at the various stages of the life cycle in the production of fertilizers and chemicals; by farm machinery during field operation—planting, spraying, and harvesting; and by vehicles used to transport the input products to farm gates. Potential emissions along the logistics of transporting off the farm, exporting, or marketing the grain products were not included in this study because they were considered the same for all crop management practices evaluated. A full life cycle assessment approach may be required to estimate C footprint for a whole production-marketing chain, when needed, but this approach may not be feasible at the present time because of the complexity and heterogeneity of the agricultural sector and the amount of data needed for analysis. As more tools are becoming available in the near future, the estimation of C footprint can be made for various choices of set boundaries or at a whole system level.

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